Prospects for electroweak physics

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PROSPECTS FOR ELECTROWEAK PHYSICS

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The future of electroweak precision measurements is discussed. The priority measurements, venues where these will be performed and desired precision are first described. The measurements themselves as well as future electroweak fits are then discussed in detail.

1 Precision measurements

One could say that there are two types of electroweak (EW) measurements : those that have an influence on the indirect determination of the Higgs mass, and those which are devised to be extremely stringent tests of the Standard Model (SM). In both cases, precision plays a crucial role. The following paragraphs describe a few priority EW precision observables (EWPOs), the venues where the measurements could be performed and the precision suggested by the theoretical uncertainties.

1.1 $m_{\rm top}$

The theoretical predictions of the EW precision observables (EWPOs) contain radiative corrections which are functions of $m^2_{\rm top}$ and $\log(m_{\rm Higgs})$. The experimental error on the top mass is obviously a limiting factor for accurate theoretical predictions. Reducing the experimental error on the top mass will increase the constraint on $m_{\rm Higgs}$. Including the top mass measurement in the EW fits today reduces the error on the logarithm of the Higgs mass by 30%!

1.2 $m_{\rm W}$

The theoretical prediction for $m_{\rm W}$ is given in the following formula

$$m^2_{\rm W}(1-\frac{m^2_{\rm W}}{m^2_{\rm Z}}) = \frac{\pi\alpha(m^2_{\rm Z})}{\sqrt{2}G_{\rm F}}\frac{1}{1-\Delta r}. \quad (1)$$

Δr is the term summarising the radiative corrections, and is a function of $m^2_{\rm top}$ and $\log(m_{\rm Higgs})$. A simultaneous reduction of the errors on $m_{\rm W}$ and $m_{\rm top}$ will again bring tighter bounds on the Higgs mass.

1.3 Z pole observables

The Z pole observables are conveniently described in terms of the effective couplings

$$g^f_V = \sqrt{\rho_f}(I^f_3 - 2Q_f \sin^2\theta^f_{\rm eff}) \quad \text{and} \quad g^f_A = \sqrt{\rho_f} I^f_3 \quad (2)$$

Table 1: Some accelerators where precise EW measurements will be performed in the future.

Accelerator	Energy $\sqrt{s}$	Luminosity
Tevatron at Fermilab $p\bar{p}$	2 TeV	RunII 4-9 fb^{-1}
LHC at CERN pp	14 TeV	$\mathcal{L}_{\mathrm{low(high)}} = 10^{33(34)}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ 10 (100) fb^{-1}/year (10^7s)
Linear Colliders (e^+e^- polarised beams)	0.5-5 TeV	$\mathcal{L} = 2-6\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ 1000 fb^{-1}
GigaZs e^+e^-, $e^-\gamma$, $\gamma\gamma$, $\mu^+\mu^-$	m_{Z} or $2m_{\mathrm{W}}$ or $2m_{\mathrm{top}}$ or $> m_{\mathrm{H}} + m_{\mathrm{Z}}$...	
Lower energy e^+e^- i.e. BES, DAΦNE	< 10 GeV	

with $\rho_f = 1 + \Delta\rho + ...$ where $\Delta\rho = (3G_{\mathrm{F}}m_{\mathrm{top}}^2)/(8\pi^2\sqrt{2})$ at one loop level. The effective weak mixing angle usually chosen as the on resonance mixing angle for leptons

$$\sin^2\theta_\ell^{\mathrm{eff}} = \frac{1}{4}(1 - \frac{g_V^\ell}{g_A^\ell}), \tag{3}$$

where $f = e, \mu, \tau$, depends sensitively on m_{top} mainly through $\Delta\rho$. Its theoretical prediction will definitely be sharpened by reducing the experimental error on the top mass.

1.4 Vector boson pair production

A study of vector boson pair production at any collider is the best test of the non Abelian gauge symmetry of the SM. Any deviations from the SM predictions are an indubitable sign of new physics.

If the SM particle spectrum is enlarged as in the case of the Minimal SuperSymmetric Model (MSSM), small anomalous couplings are generated at low energy. In another case, a very heavy Higgs boson will decay into W and Z pairs. Dynamical symmetry breaking such as technicolor will also bring about large anomalous couplings or new heavy particles decaying into W and Z pairs. Searching for anomalous couplings or for new heavy particles are a good bet for finding physics beyond the SM.

1.5 The venues

Extremely precise measurements of the EWPOs are envisaged at future accelerators. Some of the venues are listed in Table 1.

1.6 Theoretical uncertainties and precision

Three types of uncertainties taint the theoretical predictions of the EWPOs : parametric, intrinsic and primordial[1]. The parametric uncertainties are those which are induced by the experimental errors of the input parameters : m_{Z}, G_F, $\alpha(m_{\mathrm{Z}}^2)$, m_ℓ, m_{quark}, m_{top}, m_{Higgs} and $\alpha_s(m_{\mathrm{Z}})$. The intrinsic uncertainties originate from the unknown higher order corrections. Finally the primordial uncertainties come from the fact that most EWPOs are not directly measurable but are related to measurable quantities by an unfolding procedure which is affected by theoretical uncertainties i.e. the W mass can be extracted from a W pair cross section measurement at threshold $\sqrt{s} \sim 2m_{\mathrm{W}}$. Usually, the aim is to have parametric uncertainties smaller than all other ones.

Table 2: Cross sections, number of events per second and per year for various processes at the LHC, for low luminosity running.

Process	σ(pb)	N(s^{-1})	N($year^{-1}$)
$W \to e\nu$	1.5×10^4	15	10^8
$Z \to e^+e^-$	1.5×10^3	1.5	10^7
$t\bar{t}$	800	0.8	10^7

2 The W boson and top quark masses

2.1 m_W at the Tevatron

At the Tevatron, the dominant W production process involves annihilation of the valence quark and anti-quark from the $p\bar{p}$ collision : $p\bar{p} \to q\bar{q}' \to W \to \ell + \bar{\nu}_\ell$, where only leptonic (e, μ) decays of the W are investigated, since the hadronic decays are lost in the QCD di-jet background. Transverse quantities are used due to the huge longitudinal background coming from the forward and backward remnants of the proton and anti-proton. The transverse mass $m_T = \sqrt{2p_T^\ell \not{E}_T(1 - \cos\phi_{\vec{\not{E}}_T - \vec{p}_T^\ell})}$ and the transverse momentum of the lepton p_T^ℓ distributions are used to extract the W mass. These two variables are rather complementary, as they are to first order and respectively, independent and lineary dependent of p_T^W, less and more sensitive to the W production process, and finally more and less sensitive to detector resolutions.

The RunI data has given an error on the W mass of 59 MeV. The projected error at the end of RunII is of the order of 25 MeV. The main systematics originate from uncertainties on : the lepton energy scale, the MC modelling of the p_T^W distribution and of the system recoiling against the W. In all cases, Z events are used to reduce these uncertainties, and Z statistics end up being the dominant systematic source.

2.2 m_W at the LHC

The same method as the Tevatron is used to extract the W mass at the LHC. One expects approximately 2.3 (23) minimum bias events per beam crossing at low (high) luminosity, such that precision measurements at the LHC will rather be performed at low luminosity. Large statistics for various processes will be available and some numbers are listed in Table 2.

Considering the fact that 60 million W bosons will be selected each year, the statistical error on the W mass should be below 2 MeV. The total error is projected to be of the order of 15 MeV and will be dominated by the systematics. The main uncertainty originates from the knowledge of the lepton energy scale, which is projected to be known to 0.02%. The resolution on the lepton energy is expected to be of the order of 1.5%.

2.3 m_{top} at the LHC

The top mass will have been measured at the Tevatron with a precision of the order of 2-3 GeV. The production process for top pairs at the LHC is mainly via gluon fusion $gg \to t\bar{t}$ (90%) but also through quark-anti-quark annihilation $q\bar{q} \to t\bar{t}$ (10%).

The cross section at the LHC is approximately 830 pb (7 pb at the Tevatron) yielding 8 million events per year. The top quark decays almost always into a W boson and a b quark, such that the two W bosons originating from the top and anti-top will decay either both hadronically (44%), both leptonically (4.9%) or semileptonically (one W decaying hadronically, the other leptonically; 29.6%). Leptonic decays only include the electron and muon channels, but not the tau.

The final error is expected to be of the order of 1 GeV. The main systematic error originates from the light and b jets energy scale, which will be determined using $\mathrm{W} \rightarrow \mathrm{jj}$ decays in $\mathrm{t\bar{t}}$ events as well as Z+jets events, and it is expected that a 1% uncertainty can be reached. The other important systematic error originates from Final State Radiation (FSR) effects, and may be large. Complete studies have not yet been performed.

2.4 m_{W} *and* m_{top} *at linear colliders*

At a linear collider (LC), the W boson and top quark masses will be determined, amongst other methods, via threshold scans. Indeed, the cross section at threshold (e.g. σ_{WW} at $\mathrm{E_{cm}} \sim 2m_{\mathrm{W}}$) is highly dependent on the mass of the particle produced. These scans would be performed at a GigaZ LC.

The absolute beam energy will have be to known to a precision of less than 2.5 MeV if a final error of 5 MeV on the W mass is to be achieved. As an example, the threshold scan would imply 100 fb^{-1} of data taken over six energy points, representing one year of data taking. At energies higher than the threshold, the direct reconstruction method would give a 10 MeV error with 500 pb^{-1} at $\mathrm{E_{cm}} = 500$ GeV.

For the top mass, the problem is a bit more complex due to the fact that it is impossible to extract a free quark, and hence the quark mass definition already starts out with a primordial theoretical uncertainty (from the unfolding procedure, which unfolds the top mass from the $\mathrm{t\bar{t}}$ cross section measurement) of several hundred MeV. The big shifts in the peak position between leading order, next-to-leading and next-to-next-to-leading, can be attenuated by introducing a new definition of the top mass [2], less sensitive to these shifts : $E_{1s} = 2m_{\mathrm{top}}^{\mathrm{pole}} - V_{\mathrm{t\bar{t}}}(\alpha_{\mathrm{s}})$, where E_{1s} is the cross section peak position and defines the new top mass, $m_{\mathrm{top}}^{\mathrm{pole}}$ is the top quark pole mass previously defining the top mass, and $V_{\mathrm{t\bar{t}}}(\alpha_{\mathrm{s}})$ is the $\mathrm{t\bar{t}}$ binding potential. Using this definition, the top-anti-top cross section $\sigma_{\mathrm{t\bar{t}}}$, the top momentum p_{top} and the forward-backward asymmetry A_{FB} are simultaneously fit to the data in order to extract the *1S potential subtracted* top mass, the strong coupling constant $\alpha_s(m_{\mathrm{Z}})$ and the top width Γ_{top}. In a ten point energy scan and with a total of 300 fb^{-1} of data, errors of 100 MeV, 0.0012 and 20 MeV can be achieved for m_{top}, $\alpha_s(m_{\mathrm{Z}})$ and Γ_{top} respectively. The precision of the result is limited by QCD effects of the order of Λ_{QCD}.

3 The effective weak mixing angle $\sin^2\theta^l_{\mathrm{eff}} = (1/4)(1 - g^l_V/g^l_A)$

The effective weak mixing angle has been extracted from the SLD and LEP Z-pole leptonic asymmetry measurements and is given by $\sin^2\theta^\ell_{\mathrm{eff}} = 0.23150 \pm 0.00016$. It is the strongest constraint on the Higgs mass today, and similar or better uncertainties will be achievable at hadron and linear colliders.

3.1 Tevatron

The weak mixing angle is determined by measuring the forward-backward asymmetry in Drell-Yan produced lepton pairs near the Z pole $\mathrm{p} + \bar{\mathrm{p}} \rightarrow \gamma/\mathrm{Z} \rightarrow \ell^+\ell^-$. The asymmetry is defined by $A_{\mathrm{FB}} = (\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})/(\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})$ where $\sigma_{\mathrm{F(B)}} = \int_{0(-1)}^{1(0)} d\cos\theta^*(d\sigma/d\cos\theta^*)$. The angle θ^* is the one defined by the lepton and the polar axis, and this axis is determined by taking the bisector of the proton momentum and the negative of the anti-proton beam momentum when they are boosted into the $\ell^+\ell^-$ rest frame. In $\mathrm{p\bar{p}}$ collisions at Tevatron energies, the flight direction of the incoming quark coincides with the proton beam direction for a large fraction of events. In the limit of vanishing di-lepton p_T, θ^* coincides with the angle between the lepton and the incoming proton in the $\ell^+\ell^-$ rest frame.

It has been shown [4] that the asymmetry can be expressed as a function of the weak mixing angle as follows $A_{\rm FB} = b(a - \sin^2\theta^\ell_{\rm eff})$ where a and b take into account the radiative corrections as well as the experimental cuts.

Using the electron and muon channels, with 15 $\rm fb^{-1}$ per experiment at the Tevatron (CDF and D0), a statistical error of $\Delta^{\rm stat}\sin^2\theta^\ell_{\rm eff} \sim 2.3\times10^{-4}$ can be achieved. The systematics will be dominated by the uncertainties on the parton distribution functions (PDFs) but are expected to be smaller than the statistical error.

3.2 LHC

At the LHC, Drell-Yan di-leptons are also used to extract the weak mixing angle, but because it is a proton-proton machine, the anti-quark will always come from the sea. The quark direction in the initial state has to be extracted from the boost direction of the di-lepton system with respect to the beam axis.

At the LHC, the sea-sea quark flux is much larger than at the Tevatron. As a result, the probability $f_{\rm q}$ that the quark direction and the boost direction of the di-lepton system coincide is significantly smaller than one. The forward-backward asymmetry is therefore smaller than at the Tevatron. Events with a large rapidity of the di-lepton system $y(\ell^+\ell^-)$ originate from collisions where at least one of the partons carries a large fraction x of the proton momentum. Since valence quarks dominate at high values of x, a cut on the di-lepton rapidity increases $f_{\rm q}$, and thus increases the asymmetry and the sensitivity to the effective weak mixing angle.

The expected statistical error on the LHC weak mixing angle measurement is of the order of $\Delta^{\rm stat}\sin^2\theta^\ell_{\rm eff} \sim 1.4\times10^{-4}$ per experiment for an integrated luminosity of 100 $\rm fb^{-1}$. The largest systematics originate from the uncertainties on the parton distribution functions, the lepton acceptance and the radiative corrections.

3.3 LC

At an $\rm e^+e^-$ linear collider, the weak mixing angle will be determined most accurately by measuring the left-right asymmetry $A_{\rm LR}$ of hadronically decaying $\gamma/{\rm Z}$ events at the Z peak center-of-mass energy (GigaZ LC option). If in addition it is possible to have not only a highly polarised electron beam ($P_{\rm e^-} = 80\%$) as was done at the SLC, but as well a polarised positron beam ($P_{\rm e^+} \sim 60\%$), then one can determine $A_{\rm LR}$ by measuring the cross section for the four possible beam helicity combinations, as is suggested in the Blondel scheme [6]. Assuming equal absolute polarisation values of bunches with opposing helicity states, the following equation is obtained.

$$A_{\rm LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}} \tag{4}$$

with $\sigma_{++} = \sigma_{\rm u}[1 - P_{\rm e^+}P_{\rm e^-} + A_{\rm LR}(P_{\rm e^+} - P_{\rm e^-})]$, $\sigma_{-+} = \sigma_{\rm u}[1 + P_{\rm e^+}P_{\rm e^-} + A_{\rm LR}(-P_{\rm e^+} - P_{\rm e^-})]$, $\sigma_{+-} = \sigma_{\rm u}[1 + P_{\rm e^+}P_{\rm e^-} + A_{\rm LR}(P_{\rm e^+} + P_{\rm e^-})]$ and $\sigma_{--} = \sigma_{\rm u}[1 - P_{\rm e^+}P_{\rm e^-} + A_{\rm LR}(-P_{\rm e^+} + P_{\rm e^-})]$. Although an absolute polarisation measurement is not needed, polarimeters are still necessary in order to measure the relative polarisations within one beam.

A statistical error of $\Delta^{\rm stat}\sin^2\theta^\ell_{\rm eff} \sim 1\times10^{-5}$ seems feasible [5], using 10^9 hadronic Z decays (70 days running at $\mathcal{L} = 5\times10^{33}{\rm cm^{-2}s^{-1}}$ and $\rm E_{cm} = m_Z$), with $P_{\rm e^-} = \pm80\%$ and $P_{\rm e^+} = \pm60\%$.

3.4 $\sin^2\theta^l_{\rm eff}$ in general

The statistical error on the weak mixing angle achievable by a linear collider is smaller by one order of magnitude than the parametric uncertainty induced by today's experimental error on $\alpha(m^2_{\rm Z})$. Indeed, today's error on the hadronic contribution to the electromagnetic constant,

Table 3: Charged TGC 95% confidence intervals from the LEPII data and those expected for the LHC (30 fb^{-1}, ATLAS), and for the TESLA LC ($\sqrt{s} = 800$ GeV, 1500 fb^{-1}).

LEP2 limits	LHC 30 fb^{-1} ATLAS	TESLA 800GeV, 1500 fb^{-1}
$-0.059 < \lambda_\gamma < 0.026$	$-0.003 < \lambda_\gamma < 0.003$	$-0.0002 < \lambda_\gamma < 0.0002$
$-0.105 < \Delta\kappa_\gamma < 0.069$	$-0.07 < \Delta\kappa_\gamma < 0.08$	$-0.0001 < \Delta\kappa_\gamma < 0.0001$
$-0.052 < \Delta g_1^{\mathrm{Z}} < 0.034$	$-0.006 < \Delta g_1^{\mathrm{Z}} < 0.010$	
	$-0.0065 < \lambda_{\mathrm{Z}} < 0.0066$	
	$-0.10 < \Delta\kappa_{\mathrm{Z}} < 0.12$	

by far the largest, induces an error on the weak mixing angle as follows : $\delta\Delta\alpha_{\mathrm{had}} = 36 \times 10^{-5}(2004) \rightarrow \Delta\sin^2\theta^{\ell}_{\mathrm{eff}} \sim 16 \times 10^5$.

If the theoretical prediction of the weak mixing angle is to be as precise as the measurement itself, then it is clear that the error on the hadronic contribution will have to be greatly reduced i.e. $\delta\Delta\alpha_{\mathrm{had}} = 5 \times 10^{-5} \rightarrow \Delta\sin^2\theta^{\ell}_{\mathrm{eff}} \sim 1.8 \times 10^5$. To do so, one definitely has to reduce the experimental error on $R(s) = \sigma(\mathrm{e^+e^-} \rightarrow \mathrm{hadrons})/\sigma(\mathrm{e^+e^-} \rightarrow \mu^+\mu^-)$ for center-of-mass energies below 10 GeV, as is done for example at BES [7].

4 Gauge boson self-interactions sensitive to new physics

Triple Gauge Couplings (TGCs) are discussed here but Quartic Couplings (QGCs) can also be studied. The most general Lorentz invariant parametrisation for charged TGCs (WWγ and WWZ) gives 14 couplings, 7 per vertex. By requiring electromagnetic gauge invariance and C, P and CP invariance, 5 free parameters are left : $g_1^{\mathrm{Z}} - \kappa^{\mathrm{Z}} - \kappa^\gamma$ (SM=1) and $\lambda^{\mathrm{Z}} - \lambda^\gamma$ (SM=0). Anomalous couplings grow as $\sqrt{s}$ (κ) and s (g, λ), where $\sqrt{s}$ is the hard scattering process center-of-mass energy.

In the case of SM TGCs, the scattering processes respect unitarity. Anomalous TGCs (ATGCs) spoil the gauge structure of the model. Departure from this structure can violate unitarity at relatively low energies and so it has become standard to introduce protection in the effective Lagrangian for triple gauge boson vertices by expressing the anomalous couplings as scale dependent form factors, which are suppressed at high energy. The TGCs are then written as $TGC/(1 + s/\Lambda^2)^2$ where the scale Λ is set to 2 TeV at the Tevatron, and 10 TeV at the LHC.

At the LHC, studies have been performed by looking at W$\gamma \rightarrow \ell\nu\gamma$ and WZ $\rightarrow \ell\nu\ell\ell$ events [8]. The experimental sensitivity will come from an increase in the production cross section σ_{prod} as well as from an alteration of the differential distributions. These effects are enhanced as $\sqrt{s}$ grows. The TGCs can be extracted by using a maximum likelihood method. Table 3 summarizes the 95% confidence intervals from the LEPII data, and those expected for the LHC (30 fb^{-1}, ATLAS only) and for the TESLA linear collider ($\sqrt{s} = 800$ GeV, 1500 fb^{-1}) [9].

5 EW global fit

Both the input parameters (for the list, see Section 1.6) and the EW precision observables are used as constraints in the EW fits, but the input parameters are treated as fit parameters while the EWPOs theoretical predictions are computed in terms of these. The only unknown is the Higgs mass which comes out as a result of the fit, with the assumption that the SM correctly describes the experimental measurements.

Today, the Higgs mass constrained in the EW fits [10] is given by $m_{\mathrm{Higgs}} = 113\pm^{62}_{42}$ GeV, with a 95% confidence level upper limit of 237 GeV, using the EWPOs data in the following way :

Table 4: The present and projected accuracies for some EWPOs.

	Now	Tevatron Run IIA 2 fb^{-1}	LHC	GigaZ LC
$\Delta \sin^2\theta^{\ell}_{\mathrm{eff}}$ $(\times 10^5)$	16	78	14 – 20	1.3
Δm_{W} [MeV]	34	27	15	5
Δm_{top} [GeV]	4.3	2.7	1.0	0.1

Table 5: Higgs mass contraint for present and future EWPOs accuracies.

$\delta m_{\mathrm{Higgs}}/m_{\mathrm{Higgs}}$	m_{W}	$\sin^2\theta^{\ell}_{\mathrm{eff}}$	all data
Now	106%	60%	58%
Tevatron Run IIA 2fb^{-1}	72%	39%	35%
LHC	22%	25%	18%
GigaZ LC	12%	8%	8%

- the ZFITTER and TOPAZ0 programs have been used to perform the fit;
- a value of $\Delta\alpha^{(5)}_{\mathrm{had}} = 0.02761 \pm 0.00036$ has been used;
- low Q^2 measurements were excluded from the fit : $\sin^2\theta_{\mathrm{W}}$ from NuTeV as well as atomic parity violation measurements.

The quality of the fit is given by $\chi^2/d.o.f. = 16.3/13$ which gives a probability of 23%. The LEPII Higgs mass exclusion limit is given by $m_{\mathrm{H}} > 114.4$ GeV at 95% confidence level.

The present and projected accuracies for some EWPOs measurements are summarized in Table 4. The most precise ones obtained at a GigaZ LC require reducing the errors on the input parameters $\delta\Delta\alpha_{\mathrm{had}} = 7 \times 10^{-5}$ and $\Delta\alpha_{\mathrm{s}} = 0.0010$, such that the induced parametric uncertainties are of the same order of magnitude as the experimental errors. They also require reduced primordial (unfolding procedure) and intrinsic (higher order) theoretical uncertainties.

These results can be translated into constraints on the Higgs mass, as summarized in Table 5 [11]. The constraints are obtained from m_{W} or $\sin^2\theta^{\ell}_{\mathrm{eff}}$ alone, and from all the data. It is assumed, except for the first row, that complete two loop results will be available and that the uncertainties from the higher order corrections will be reduced by a factor 2, giving intrinsic theoretical uncertainties of $\delta m_{\mathrm{W}} = 3$ MeV and $\delta\sin^2\theta^{\ell}_{\mathrm{eff}} = 1.7 \times 10^{-5}$ using $\delta\Delta\alpha_{\mathrm{had}} = 7 \times 10^{-5}$ and $\Delta\alpha_{\mathrm{s}} = 0.0010$.

6 Conclusion

The Standard Model has been well served by precision EW measurements. Its consistency has been tested with great accuracy (to the per-mil), the SM Higgs mass is now constrained to $\pm$ 50%, and no deviations have been observed. In order to constrain the physics hopefully hiding at higher scales (i.e. Higgs, SUSY) or to precisely measure the physics bold enough to make itself seen, EW precision measurements will continue to be of prime importance.

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